

LAG OF THERMOMETERS AND THERMOGRAPHS FOR AIRCRAFT¹

By H. B. HENRICKSON and W. G. BROMBACHER

[Bureau of Standards, U. S. Department of Commerce]

The time lag of thermometers used to measure air temperatures may be of considerable importance in cases where the temperature to be measured may be changing rapidly. Data on the time lag of various types of thermometers designed for installation on aircraft for the measurement of air temperatures would therefore be of value in the design and selection of instruments for such measurements. Measurements were made of the time lags of a representative group of instruments selected from those available in the laboratory. This work was undertaken in the course of the development of aircraft thermometers for the National Advisory Committee for Aeronautics and the Bureau of Aeronautics, United States Navy, and acknowledgment is here made of their financial assistance.

It is known that the lag is dependent upon the velocity of the air stream to which the temperature element is exposed. The values reported here were for an exposure of the element in an improvised wind tunnel in which a maximum velocity of 17 miles per hour could be maintained. The data are therefore chiefly of value in determining the relative lags of the various instruments, but it is also possible from available data to estimate the order of magnitude of the various lags at customary flying speeds.

A detailed discussion of the question of thermometric lag is given in a paper by Harper.² In general, a problem of thermometric lag can be treated with sufficient accuracy by assuming that Newton's law of cooling applies—that is, that the rate of change in the temperature of the thermometer is proportional to the difference between this temperature and that of the surrounding medium. If T be the indication (temperature) of the thermometer, t the time and U the temperature of the medium, Newton's law is expressed by the equation:

$$\frac{dT}{dt} = \frac{1}{\lambda} (U - T) \quad (1)$$

The equation is written so as to make λ a positive constant, for if λ is positive, and U is higher than T , dT/dt will also be positive. The constant of proportionality is written in the form $1/\lambda$ for convenience, because when so written λ can be interpreted in a simple and useful manner. Two such interpretations are given by Harper (p. 662):

(1) If a thermometer has been immersed for a long time in a bath whose temperature is rising at uniform rate, λ is the number of seconds between the time when the bath attains any given temperature and the time when the thermometer indicates this temperature. In other words, it is the number of seconds the thermometer "lags" behind such a temperature.

(2) If a thermometer be plunged into a bath maintained at a constant temperature (the thermometer being initially at a different temperature), λ is the number of seconds in which the difference between the thermometer reading and the bath temperature is reduced to e^{-1} times its initial value.

e is the base of natural logarithms and equals 2.718.

Definition (1) is of especial importance in aeronautics. In the performance testing of aircraft a maximum rate of climb is usually maintained, and therefore the tempera-

ture of the free air in the vicinity of the aircraft is decreasing. Assuming the maintenance of a steady rate of climb of the aircraft, the following relation will hold when conditions become steady:

$$T - U = -r\lambda \quad (2)$$

where U is the air temperature, T the indication of the thermometer, r the rate of change of free air temperature per second and λ the lag of the thermometer. Thus, for example, assume that an airplane climbs at a rate of 3,000 feet per minute in an atmosphere in which the average conditions of free-air temperature exist. The value of r is then approximately 0.1°C. per second. Further, assume that the lag, λ , of the thermometer when exposed to the free air moving at the air speed of the airplane is 10 seconds. Inserting these values in equation (1) it is seen that $(T - U)$ equals 1°C. , which means that the indication of the thermometer lags 1°C. behind the free-air temperature. If the lag is assumed to be 30 seconds, the indication lags 3°C.

METHOD OF DETERMINING LAG AND EXPERIMENTAL PROCEDURE

The following relation is given by Harper (see previous reference) as the basis for the method here used of determining lag:

$$\lambda = \frac{t}{\log_e \frac{T_0 - U_0}{T - U_0}} \quad (3)$$

in which T_0 is the indication of the thermometer when the time, t , equals zero and T its indication at time t , while the thermometer is immersed in a bath at temperature U_0 . This relation is subject to certain assumptions which are valid for the determinations here reported.

The temperature elements of the thermometers under tests were brought to a temperature $T_0 = 0^\circ \text{C.}$ and then suddenly immersed in an air stream of a wind tunnel at room temperature U_0 , which was approximately $+25^\circ \text{C.}$ Observations were made of the changing readings of the thermometer at known intervals of time. The temperature of the air in the wind tunnel, U_0 , was also carefully noted and was found to be constant during the short period of time required to obtain the wind tunnel observations, usually about one minute. Any inaccuracies in this connection would appear in a marked departure from a straight line of the points at the right end of such curves as are plotted in Figure 1.

The wind tunnel consisted of a cardboard tube 10 inches in diameter built around two electric fans, one placed at each end of the tunnel. An opening was cut in the middle of the tube and a French Pitot-Venturi nozzle of known calibration was inserted in order to measure the air speed. The pressures developed by the nozzle were observed on a water manometer. On 110 volts the fans gave an air speed of 10 m. p. h.; on 220 volts, an air speed of 17 m. p. h.

Thin sheet-metal containers, just large enough to hold the various thermometer bulbs, were used to keep the bulbs dry while packed in cracked ice.

¹ Published by permission of the Director of the National Bureau of Standards of the U. S. Department of Commerce.

² Thermometric Lag, Bulletin, Bureau of Standards 8, p. 659-714, 1912 (S. 185).

The bulbs of all indicating instruments were placed in the wind tunnel so that the long axis of the instrument or element was at right angles to the long axis of the wind tunnel. The principal planes of the temperature elements of the thermographs were parallel to the axis of the wind tunnel during the tests.

RESULTS

The elapsed time in seconds plotted against the expression

$$\log_{10} \frac{T_o - U_o}{T - U_o}$$

for an air speed of 17 m. p. h. is shown in Figure 2 for each instrument. The slope of any line when multiplied by 0.434 in order to obtain logarithms to base e is the lag in seconds. A brief description of the instruments, including values determined for the lag, is given below.

A: A liquid-in-glass column-type instrument designed for use as a strut thermometer. The corrugated cylindrical bulb was unusually large (1.75 inches long by 0.43 inch in diameter) and contained a considerable mass of liquid. It was protected by a metal shield which was perforated so as to permit air flow around the bulb. Similar to instrument shown in Figure 10 of National Advisory Committee for Aeronautics Technical Report No. 126 on Altitude Instruments. Lag, 57 seconds.

B: A thermograph with a liquid-filled Bourdon tube for the temperature element. The tube (2.25 inches long, 0.62 inch wide, and 0.06 inch thick) had a considerable mass of metal as well as liquid. Lag, 33 seconds.

C: A strut thermometer. This instrument was similar to instrument **A** above, including also the protective covering of the bulb, except that the bulb was rather long, thin, and flat (3.25 inches long and 0.5 by 0.19 inch in cross section), and had somewhat less mass. Lag, 32 seconds.

D: An ordinary "chemical" mercury-in-glass thermometer. The bulb was rather small (0.5 inch long by 0.19 inch in diameter). Lag, 18 seconds.

E: An electric resistance thermometer. The temperature element, T , mounted on top of the wind tunnel, was a No. 36 silk-covered nickel wire wound upon a thin metallic tube (2.25 inches long by 0.62 inch in diameter). The resistance was 205 ohms at room temperature. Holes had been bored into the outside protecting tubing so as to reduce the lag. The temperature lag for this particular bulb was found to be 17 seconds (the average of six determinations) at an air speed of 17 m. p. h. and 22 seconds (average of two determinations) at an air speed of 10 m. p. h.

F: A thermograph with a bimetallic strip temperature element (2.5 inches long, 1 inch wide, and 0.023 inch thick). This instrument, as expected, had the lowest

thermometric lag of all the instruments so far tested. Lag, 13 seconds.

Data given by Harper for a "chemical mercury thermometer" cover a range from 0 to about 24 miles per hour. Extension to flying speeds involves a very considerable extrapolation, but by plotting $1/\lambda$ against log speed, the curve can be approximately rectified, and extrapolation of this rectified curve indicates that at flying speeds the lags would be approximately half of those determined at the air speed of 17 m. p. h. The data for two speeds given for instrument **E** also indicate that at flying speeds the lag would be about half that determined at the lower speeds.

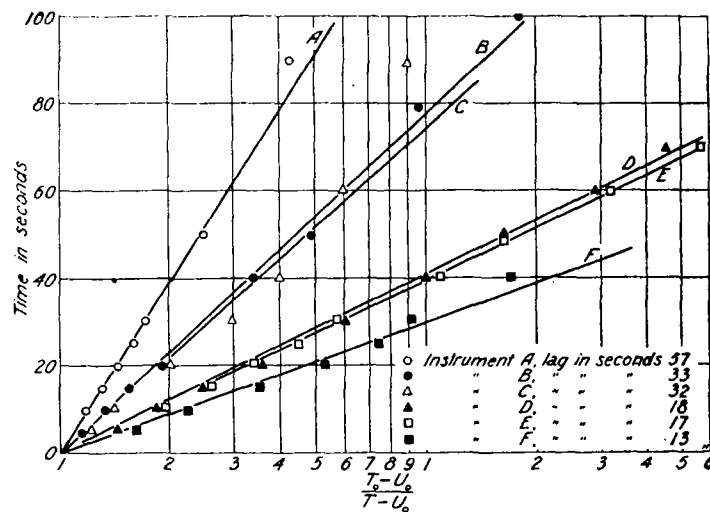


FIG. 1.—Curves obtained in determining the lag in an air stream of 17 m. p. h. Values of the lag are included.

A: Strut thermometer, liquid in glass, bulb inclosed.
 B: Thermograph, Bourdon-tube element.
 C: Strut thermometer, liquid in glass, bulb inclosed.
 D: "Chemical" thermometer, mercury in glass.
 E: Electric resistance thermometer.
 F: Thermograph, bimetallic strip element.

SUMMARY

The thermometric lag of six aircraft temperature instruments ventilated by an air stream of 17 m. p. h. was determined with the following results:

A: Strut thermometer, liquid in glass, bulb inclosed, 57 seconds.

B: Thermograph, Bourdon-tube element, 33 seconds.

C: Strut thermometer, liquid in glass, bulb inclosed, 32 seconds.

D: "Chemical" thermometer, mercury in glass, 18 seconds.

E: Electric resistance thermometer, 17 seconds.

F: Thermograph, bimetallic strip element, 13 seconds.

In general, the liquid-filled types have lags which are excessive for aircraft use.